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IVHM (Integrated Vehicle Health Management) Techniques for Future Space Vehicles

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Abstract

NASA's Integrated Vehicle Health Management (IVHM) Program will lay the groundwork for the next generation of space vehicles. By integrating artificial intelligence with advanced sensor and communication technologies, spacecraft can built that can reason, diagnose problems, and recommend solutions, giving human crews more time for the important work of exploring space.

IVHM has the potential to reduce, or even eliminate, many of the costly inspections and operations activities required by future space transportation systems. The development and utilization of an effective and operable IVHM is dependent on the availability of highly reliable sensors and decision-making software. Inadequate or faulty sensors have resulted in premature termination of engines and failure to detect structural defects in flight critical components. Accurate and reliable sensors are fundamental to the development of systems to monitor and manage the structural status and operation of space transportation systems. Historically, sensors have been a major operations cost item and yet they have been greatly overlooked during the critical design and development of transportation systems and components.

This paper will discuss IVHM techniques for future space vehicles. It will give a broad overview to the subject and value of IVHM as well as discuss the challenges and opportunities.

Introduction

The concept of fully reusable Earth-to-orbit access vehicles stress "requirements" for hardware that is operationally friendly. Whether civilian or military in origin, capabilities such as low cost launch and general-purpose planetary transport platforms are espoused by nearly everyone in the "space use for research and commercialization" field. Many technologies not now employed or developed will be required to implement such a vision. The emphasis here is on the vision aspect of the "requirements" inasmuch as these are seen as necessary for vehicles to be available in the long range, that is 20 years or so from now. Since no commercial entity or governmental agency – or government for that matter – can reasonably afford to develop a complete system on their own, the basic necessary subsystems will have to be created over the next few years in preparation to producing the final vehicle(s).

It is considered by many that the only way to assure the goals of such concepts will be to include an integrated capability for automating the maintenance and operation of such vehicles. That would mean a significantly different use of avionics systems as opposed to the way they are now employed. This is the concept of Integrated Vehicle Health Management (IVHM) as opposed to simply "IVH Monitoring." Such a concept implies the ability to fully monitor the operational functions of the target vehicle and to have built-in systems abilities to do something with the information derived from that monitoring.

Another critical aspect of IVHM is that information is generated and acted upon rather than merely acquiring data and presenting it for later manipulation and use. The integrated system will require many modules as subcomponents such as structural surveillance systems, active structural controls and adaptation, flight controls and control surfaces, propulsion management and surveillance, guidance and navigation. This paper is intended to present some guidance on the direction of thought processes needed to develop the referenced systems.

BACKGROUND AND DESCRIPTION

IVHM has gone through a series of names and terms. Currently, different organizations still use different terms to describe essentially the same functions. Historical name changes include:

- FDIR – Fault Detection, Isolation and Reconfiguration (aerospace Industry 60s/70s)
- Autonomy – (some believe that IVHM is a subset of autonomy and there are those who believe that autonomy is a subset of IVHM)
- VHM – Vehicle Health Monitoring (evolved from FDIR)
- SHM – Systems Health Management (first attempt to integrate safety, reliability, fault management, testability and cost benefit analysis into a common framework through SE&I). Also defined independently as Structural Health Management
- VHM – Vehicle Health Management (management aspect spans autonomous reconfiguration as well as the resources required to safely and most cost effectively achieve mission goals)
- IVHM – Integrated Vehicle Health Management ("I" reflects the systems health management approach spanning all elements/all program phases)
- IM – Informed Maintenance (condition based maintenance)
- RSO – Resilient Systems & Operations (Level 2 IVHM project under the Design for Safety Program)

IVHM is a NASA-wide effort to coordinate, integrate and apply advanced software, sensors and design technologies to increase the level of intelligence, autonomy and health state determination and response of future vehicles.[1] It includes the trades and decision-making processes that determine the specifications and implementation of the requirements. It is the particular sensors, processors, data storage, data communication, software and algorithms, which are used to detect, predict, isolate, report on, and manage the health of the vehicle system.

IVHM needs to be designed into the system using traditional system engineering practices to optimize mission and program goals (i.e., safety, mission reliability, life cycle costs, etc). It consists of intelligent, system-level assessment, control, and management solutions to inform and assist vehicle and mission operators in mitigating life-cycle risks and unanticipated hazards during operations.

Research within this element will focus on in-flight or on-operation strategies to ensure mission success such as integrated vehicle health assessment and management; adaptive and/or autonomous control schemes; and human-machine advisories and interfaces. This element will also develop integrated system testing and validation technologies and system servicing and processing solutions to mitigate risks throughout the system life cycle.

One of the early and still persistent criticisms of IVHM (or whatever it was known at the time) is that it simply calls for increased instrumentation of the subsystem. This did not go over well with the subsystem people who felt (and still feel) that sensors are part of the problem, not part of the solution and adding more simply makes things worse, not better. This feeling has been borne out, unfortunately, in that inadequate or faulty sensors have resulted in premature termination of engines and failure to detect structural defects in flight critical components. One of the major goals of IVHM is to convince the subsystem people that sensors and the information they provide are part of the solution, not the problem.

The strategy to accomplish this is shown as Figure 1. At the beginning of a new project or subsystem, few verified models exist. To provide validation and fidelity to these models, instrumentation is necessary. As the models achieve more fidelity, less instrumentation is required until, for the production version, only the proper instrumentation necessary for maintenance should remain.

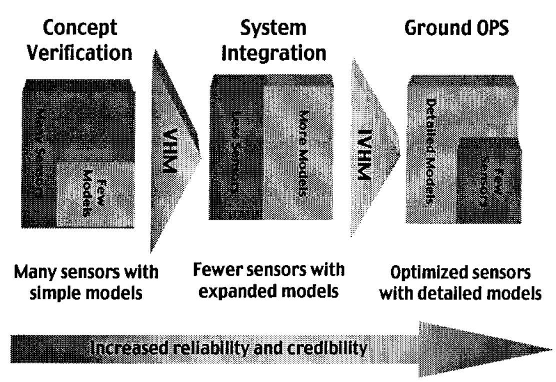


Figure 1. Improvements if IVHM introduced early.

Figure 2 shows another concept of IVHM, i.e., the flow of information, from signals through information to wisdom, which can then be used to filter down to the actual physical measurements required for vehicle health.

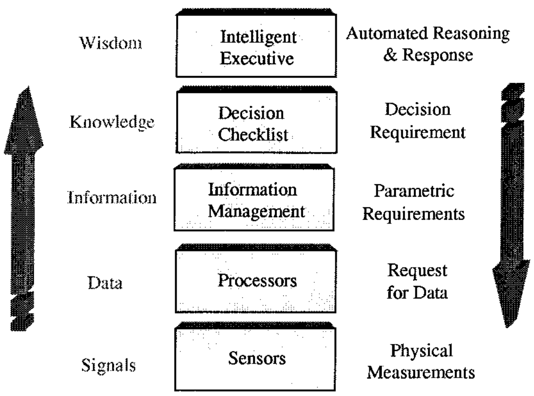


Figure 2. RSO/IVHM Strategy: Autonomously Convert Sensor Signals to Wisdom.

DEVELOPMENT ACROSS THE GENERATIONS

NASA's view of the current and future generations of space vehicles is shown in Figure 3. The Space Shuttle is the first generation vehicle, and plans are being made to decide critical issues for the 2nd Generation Vehicle through the NASA's Space Launch Initiative (SLI) program. This paper looks at requirements for 3rd Generation vehicles, or those being fielded by 2020. NASA's strategic plan involves continued investment in future systems that will enable new markets in space.

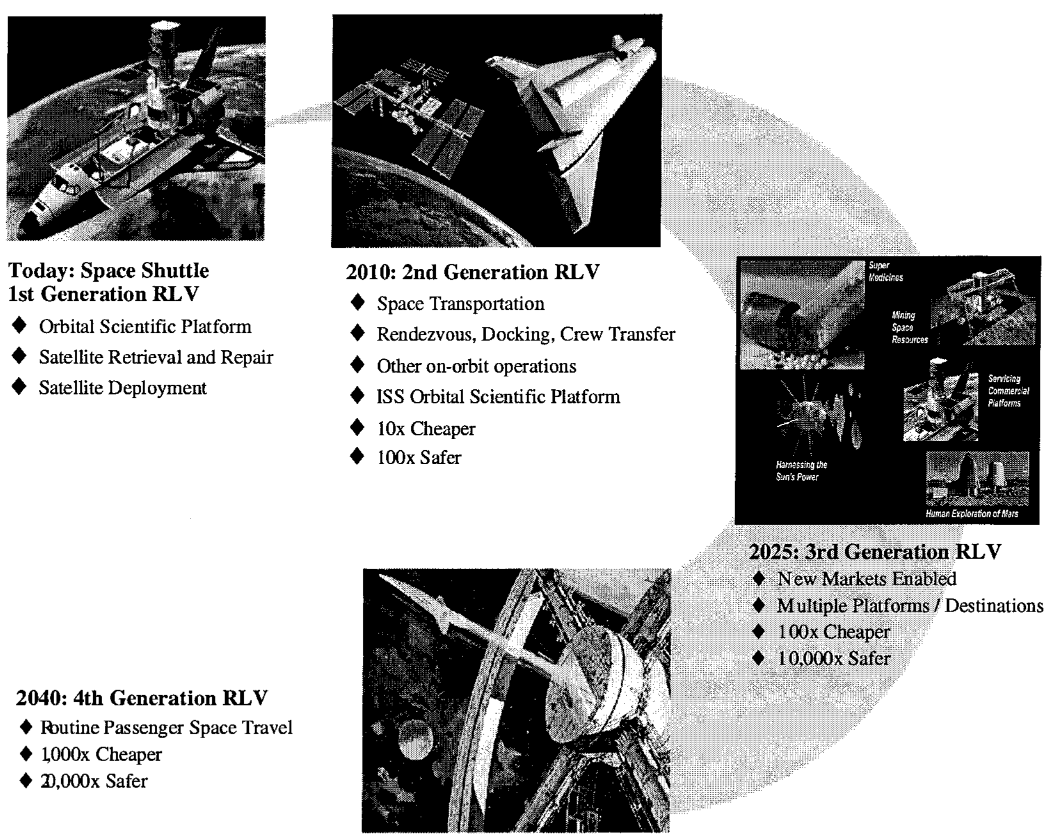
The need for a 2nd Generation system is based on three tenets:

- Investment in technical risk reduction activities, driven by industry need, to enable full-scale development of commercially competitive, privately owned and operated, Earth-to-orbit RLV's by 2005 and operations by 2010;
- Development of an integrated architecture with systems that meet NASA-unique requirements that cannot be economically served by commercial launch vehicles alone; and
- Procurement of near-term, path-finding launch services for select Space Station requirements on commercial launch vehicles.

Figure 3 also shows the overarching goals of reducing cost and increasing safety by orders of magnitude with each succeeding generation. To achieve these goals, some type of IVHM will be needed and to achieve it will require revolutionary changes in integration of hardware and software.

The following table shows the technologies maturation across the generations:

Figure 3. Generations of Space Vehicles.



1st Generation	2nd Generation	3rd Generation
Disparate, sparse subsystem/ component coverage	Major LRU coverage, limited integration	Integrated into design
Operations focused	Maintenance and operations focused	Complete system coverage
Real-time decision aids (on ground)	In-flight and post-flight analysis	Reliability, maintenance and operations focused
Post-flight analysis	Smart components - Turbopumps, nozzles...	Intelligent Propulsion System: real-time analysis fully integrated with accommodating controls, intelligent maintaining systems
Retrofitted	Advanced materials knowledge	

IVHM SCOPE AND OBJECTIVES

Figure 4 is the roadmap of IVHM. The National IVHM roadmap involves the development of crosscutting technologies that can be leveraged by all platforms including RLV, Military and civil aviation, ISS, Planetary probes, etc.

IVHM Objectives include:
- Safety
- Reliability
- Mission Assurance
- Reduced Maintenance Costs
- Efficient Vehicle Turn-Around

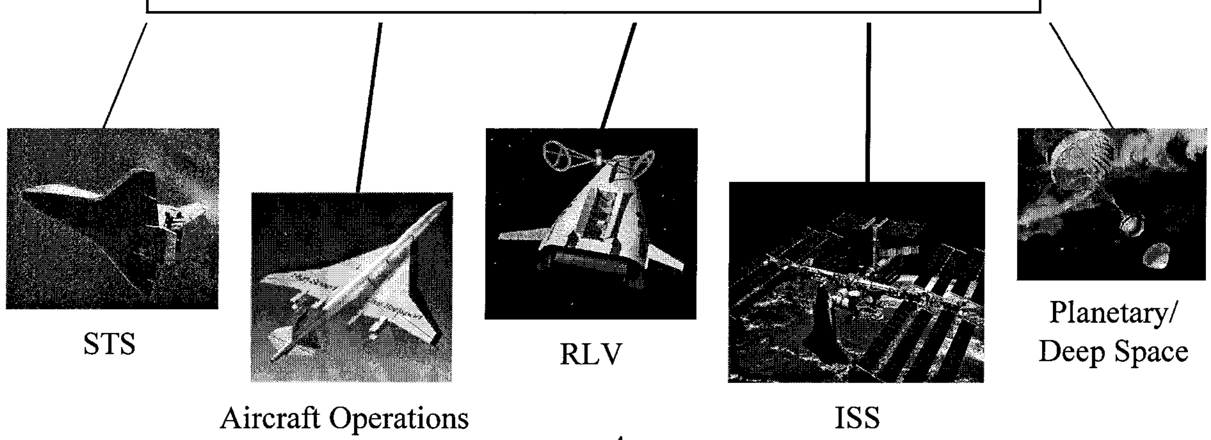
The general direction involves plans to significantly reduce operations costs and improve safety. This requires the development of health management for both maintenance and controls applications. Vehicles of all types will become progressively more intelligent with the infusion of more advanced IVHM technologies over the next decades.

The technologies being developed in the 2nd Gen program focus on Cost reduction and the Design for Safety (DFS) program focuses on Safety related to mission success, including crosscutting vehicle Health assessment tools are being developed for application to any platform. The health assessment tools combined with control technologies (i.e. Neural net controllers) will eventually enable all of the capabilities listed above the pictures.

The Intelligent Vehicles of the future will:
- Carry out a system-level self-assessment
- Do real-time adaptive control based on hazards encountered
- Plan and execute its mission
- Manage its health (RT and LT) and schedule repairs
- Interact with and/or advise humans on-board or on the ground

Figure 4. IVHM Scope.

Monitoring		Management
Reporting		Reacting
Diagnosis		Prognosis
Sensors		Intelligent Sensing
Human Control	Distributed Control	Autonomous Vehicle
Components		System
Now		**Future**



Attributes of an Avionics System For 2020

Given that a new avionics system is required to allow implementation of the concepts as previously described, what might be the attributes of such a system? Consider the following list: Inherently Safe, Operationally Reliable, Situational Cognizant Response, Maintenance Free, Mission Flexibility, Light Weight, Very Low Power, Low Life Cycle Cost.

Now consider further expansion of the above categories.

Inherently Safe -No vehicle system failures leading to loss of vehicle or human injury with probability greater than commercial airline operations.

Operationally Reliable -Operable in any natural or induced operational environment including expanded thermal operating ranges and

Inherent radiation hardness (extreme tolerance) -Dynamically reconfiguring hardware and software, -Self healing.

Situational Cognizant Response -Integrated into other systems, -cognitive abilities (automated reasoning and learning), -variable autonomy, -optimizes Human Integration and Autonomous Operations, -self-validating and self-verifying hardware and software.

Maintenance Free -No maintenance for operational life of the vehicle, -inherent health management, -no active thermal control of avionics components, -simple servicing.

Mission Flexibility -One system fits all, -Applicable to any propulsion (transportation) system-ultra high, secure bandwidth capability, -not data storage limited, -data efficient architecture for data distribution, storage and use, -functional modular designs, -scaleable & upgradeable components.

Light weight -Low Mass -avionics components embedded as fundamental components of other subsystems.

Very low power -Low power consumption (< 5% of vehicle power)

Low Life Cycle Cost -Easily configured /reconfigured, -lower operational cost, -increased vehicle functionality/performance, -increased cost/benefit ratio.

A basic concept can be extrapolated using the above list as a guide, yielding an architecture that could serve for many vehicles and lasting many years without having to redesign for each and every new application. Such a system would be composed of modules that could be assembled as required to provide complete coverage for any given situation. One could suppose sensor nodes and sensors as nodes as well as control function nodes, while supporting multi-bus redundancy. The system should support functional redundancy using only one bus medium – e.g. coax or twisted pair.

The complete system might be composed of subsystems that would be more "commercially" convenient for interfacing with the sensors, effectors, and internal (black box) health nodes. It would make sense to leverage the efforts of others in the development of busses created outside of aerospace and thus take advantage of the enormous amounts of funding expended on creating some of these new data handling systems, techniques and protocols.

Avionics for the Future

The avionics system for the future vehicles will need to be highly adaptable insofar as accommodating essentially any form of sensor one could conceive. It is likely that many sensors would have built in capabilities such as redundancy, self-checking, flexible range programming and the like. Such devices would have direct digital interfaces; systems in use today, and for that matter most that are "new", have no way to interface with such devices since, in essence, that would require "peer-to-peer" communication within the network. Future systems will need to be bi-directional multi-channel, self-powered networks offering automatic failure detection and correction.

The system envisioned would support the use of wired and wireless connections as required. Providing the power for the communication nodes from within the network would make possible significant weight reduction; in turn, providing that power would necessitate internal power management for the network. In order to reduce the gross amount of data being transferred on the network, it would be best to distribute the computing power of the system so that data can be preprocessed into limited information prior to transfer. That scheme would allow nodes to communicate directly with one another, thus not occupying time on the central computer if not necessary.

All of these goals can be met, but doing so will require a methodical, medium term development. It is not reasonable to expect anything of that nature to be ready to employ whenever desired without the up-front investment.

"Smart" Structures (Structural Health Management for Future RLV's)

Another developmental technology needed would be "smart" structures. By that is meant structural components having either embedded into or attached onto them transduction elements allowing active or passive monitoring of the physical condition of the subject. In practice, such an arrangement would permit real-time testing of panels or support members and, in some cases, active interaction with the target. Such a system could be used inside, or on the surface of, metal and non-metal structures such as panels, struts, and beams, whether they be honeycomb, composites, or monolithic in nature. Such systems would need to allow convenient construction and maintenance of the vehicle, implying few or no wiring connections to these components. The concept of embedding electronics into structures implies ingenious use of materials to account for temperature and thermal expansion effects. Also, the non-contact consideration will necessitate novel ways of coupling data and power across an interface.

Embedded testing will enable real-time surveillance of a structure, yielding the answers to questions such as: is the object under test the same as it was the previous time(s) it was viewed? Has it been hit? Has it been penetrated? Has the composite delaminated or otherwise failed? Such systems could also be used to monitor overall condition/position in feedback control loops when used with morphing surfaces, as might be employed for vehicles with configurable aerosurfaces.

RLV's are subjected to extreme conditions including large vibrations, low and high temperatures, and chemical attack (e.g., atomic oxygen, propellants, and salt air at launch sites). For the Shuttle, currently the only operational RLV, a huge amount of time, money and effort is expended to inspect for structural damage from these extreme environments. To meet reduced operational cost and improved safety goals of future RLV's, such inspections will need to be significantly reduced or eliminated through the use of on-board structural health management (SHM). To enable future SHM systems, numerous technical advances are necessary in three areas: sensors, data communication and processing systems, and data analysis.

The most significant requirement for sensor systems is to provide high sensor density for a diversity of measured parameters (e.g., strain, temperature, pressure, vibration, chemical detection, etc.) It is envisioned that tens of thousands of sensors will be needed to cover the large acreage of varied structural components such as propellant tanks, wings, fuselages, etc. To provide this large numbers of sensors and still allow the vehicle to get off the ground, the sensor systems must be extremely small and require little power. Another obvious requirement is that they be rugged and reliable in the RLV operational environment. Launch delays and mission failures as a result of sensor system failures will not be tolerable. Recent significant advances in sensor systems include the development of distributed fiber-optic sensors, MEM's and nanotechnology. The weight of 10,000 fiber-optic strain or temperature sensors is less than one pound. In a recent test of a composite wing structure, over 3000 fiber-optic strain sensors in only four optical fibers were monitored[2]. The miniature size of MEM's sensors such as accelerometers will also enable high density sensing, and nanotechnology advances will provide further reductions in sensor size and weight.[3]

The challenge for such micro/nano sensors lies in providing power and data communication. The complexity and weight of just the wiring alone for tens of thousands of single ended sensors is prohibitive for a RLV. The development of distributed systems where large numbers of sensors are supported on a single wiring system is needed. Another potential solution is wireless communication, but the transmitters must be lightweight, low power, reliable and able to withstand the harsh environments. To provide power for wireless applications, micro-battery systems are under development that can recharge from conventional sources such as solar, as well as harvest power from sources such as structural vibrations[4]. Nanotechnology developments will also impact this area through the development of significantly miniaturized processors and storage systems.

Data analysis for SHM is an area in which significant development is also needed. Methods to analyze the data from thousands of sensors to detect damage and predict structural residual life will be required. In particular, high speed and automated data analysis methodologies such as data mining, artificial intelligence, neural networks, etc. must be implemented to enable real time decision-making. Detailed structural models will provide the basis for optimization of SHM sensor placement. Another application of structural modeling will be to develop techniques to infer local structural variables such as strain from global vehicle operating parameters. Such techniques will help offset the need for as many local sensors, and help to interpolate measured results between sensors.

Over time and with the numerous technical developments described above, SHM systems will evolve as part of an overall IVHM system to meet the safety, reliability, and economic requirements of future RLV's.

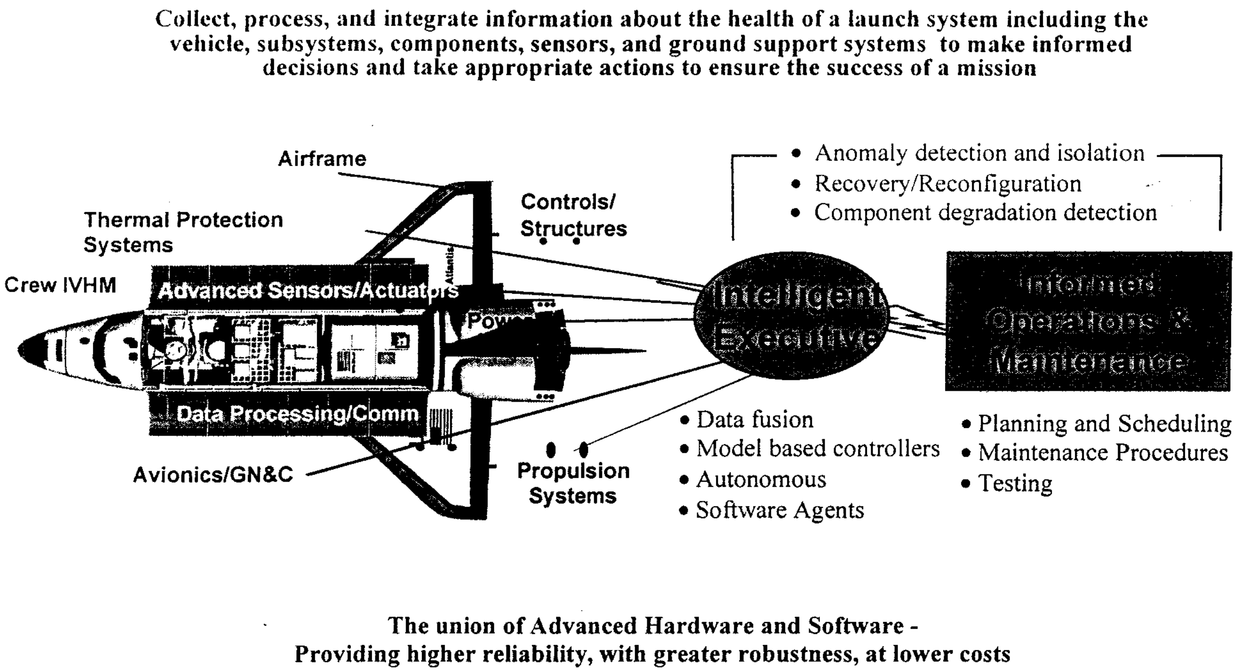


Figure 5. Informed Maintenance.

3RD GENERATION INFORMED MAINTENANCE (IM)

The concept of IM is depicted in Figure 5. The elements of IM include an integration of on-board and ground-based diagnostics/prognostics, automated maintenance scheduling, and automated logistics coordination, paperless documentation, wireless communication, decision-making tools and data mining. These technologies have potential of making significant contributions to achieving 3rd Generation Program goals of $100/lb to low Earth orbit, ground maintenance in terms of hours, improvement of catastrophic unreliability to 1 in 100,000 missions and flight vehicle life of 10,000 missions.

A vision of 3rd Generation IM is very much a departure from today's Space Shuttle ground operations.[5] While in-flight, the vehicle undergoes extensive automated in situ test and checkout of flight systems. Refined fault isolation greatly reduces post-landing troubleshooting efforts by ground operations personnel. Failure predictions allow for improved maintenance planning even several ground turnaround flows in advance. Maintenance scheduling for multiple vehicles is preplanned and optimized with automated updates. Discrete maintenance tasks on multiple vehicles are performed at optimal convenience to the ground operations personnel while maintaining safety criteria and flight rates. Since flight vehicle fleet size is well above one thousand and active missions are well above 400 at any given time, ground systems are very closely coupled and receive multiple telemetered flight vehicle health summary data prior to landing. On-board and ground-based complex diagnostic and prognostic system health determinations are performed and integrated using advanced applications such as neural networks and web based multi-mission data mining. Configuration management control requires tracking of numerous flight vehicle component life histories down to the serial number level. The ground maintenance is performed "at the gate" in terms of hours by a very small team in a paperless and wireless environment. Wearable computers are utilized with wireless access to canned maintenance procedures, vehicle schematics and historical performance data. Logistical coordination is highly automated and involves routing and staging of properly skilled personnel and equipment. Complex statistical analysis techniques support the sparing infrastructure. Lastly, there is extensive use of engineering advisory tools for near real-time decisions to support launch and ground operations through automated determination of corrective actions.

NASA is leveraging IM technology development currently underway by several organizations. The automotive industry is leading the development of on-board and ground-based diagnostics. Nissan has developed a system called the Electronic Concentrated Control System (ECCS) which provides Diagnostic Trouble Codes (DTCs) for technicians to reference in the Diagnostic Manual via CD-ROM. Similarly, Ford states that currently

70,000 technicians are using their two volume "ultimate toolbox" Service Manual by referencing on-board provided Service Codes to obtain test procedures, test guides and wiring diagrams for all unique engine configurations.[6]

Integrated Diagnostics (ID)[7] was developed by the Boeing and Honeywell Corporations for the 777 aircraft called the Aircraft Information Management System (AIMS). This integrated a number of aircraft functions, previously in separate Line Replaceable Units (LRUs), into a single central computer system including the Central Maintenance Computer (CMC). Boeing Phantomworks is developing the Informed Maintenance and Support System (IMSS) which is a maintenance concept that integrates the vehicle, maintenance scheduling, maintenance technicians, technical data, support equipment and logistics system into a tightly managed support system.

For the Joint Strike Fighter (JSF), Lockheed-Martin is developing the Joint Distributed Information System (JDIS).[8] It includes on-board Mission Systems and Vehicle Maintenance System (VMS) as well as ground based Prognostics Health and Management (PHM). JSF will integrate on-board status with ground based logistics and training databases to optimize vehicle availability. Lockheed-Martin Skunkworks' Integrated Health Management and Data Advisory Tool (IHMDAT) for X-33 is a ground-based system engineering support tool that provides console operators significant added capability for making Launch Commit Criteria (LCC) and maintenance decisions.

Informed Maintenance for the Space Shuttle has focused on Predictive Health And Reliability Management (PHARM).[9] This system collects and analyzes sensor data, trend failures, and notifies logistics when a replacement part will be required. For X-34, the NASA IVHM Technology Experiment for X-vehicles (NITEX) was to have monitored main engine parameters throughout all mission phases using detailed diagnostic algorithms to detect degraded component performance as well as a system-level health monitoring system that integrates information from multiple components to perform real-time fault detection, isolation and recovery. In addition, the experiment would have demonstrated the use of an advanced, user friendly ground station that combines information provided by the on-board IVHM software with information obtained while the vehicle was on the ground to provide high-level status information on the health of the vehicle along with the ability to access more detailed information when required.

X-37 IM is being developed by Boeing and NASA.[10] This system will focus on the health summary information provided by the IVHM flight experiment as well as additional information already available in the vehicle's telemetry stream. It will be included into an overall rapid vehicle turnaround demonstration planned utilizing a wireless work documentation system and a wireless communication system for maintenance personnel.

Finally, the Deep Space-1 spacecraft Flight Operations Control Center (FOCC) display has established the IVHM/IM standard.

INTELLIGENT SPACE PROPULSION SYSTEMS

Future propulsion systems must do things no machines have done before. Because of built-in intelligence and automation, future propulsion systems will also be easier to turn around between flights. Such propulsion systems will be characterized by greater safety and higher reliability, all for less cost.

Where does this development start? All intelligent propulsion systems will be developed by starting with requirements definition, tailored for the specific propulsion system and mission. Tools for this assessment are currently being defined, implemented and extended. These tools will be able to define which health management technologies should be included and the potential benefits.

The major functional elements currently being developed that could be included in the future intelligent propulsion systems include:

- Data acquisition, storage and distribution (both sensor and other data)
- Smart high temperature and harsh environment sensors
- Data Validation/ Reconstruction
- Anomaly Detection
- Advanced Diagnostic Analysis (model-based, vibration analysis, photographic techniques, etc.)
- Prognostics and Trending
- Condition-Based Maintenance
- Information Fusion
- Model Based Reasoning

Smart sensors in combination with an efficient data acquisition and storage strategy are the foundation for any future IVHM system. Propulsion systems however have unique sensor consideration because of the conditions that the sensor technology operates within. These conditions range from high temperature in the engine environment, to cryogenic in the fuel tank regions. Propulsion sensor technologies that combine electrical, MEMS and optical systems with built in calibration and intelligence will be necessary. New sensors for life determination are also being developed. For example, strain measurements indicate the life of the material by measuring deformation of the material and the presence of cracks. Low power, low weight and size MEMs based leak detection sensors are also being developed to detect and locate presence of leaks. Also, multi-parameter sensors that included communication capabilities are being developed as well as technologies that allow components to be instrumented with embedded sensors throughout its structure.

These smart sensors in combination with intelligent diagnostic and prognostic software allows for the management of faults and wear that occur during the operation of a propulsion system. The software systems currently being developed use a combination of artificial intelligence and classical analysis methods to provide a fast, consistent data analysis, diagnosis and prognosis. Improved model based approaches for propulsion systems are being developed and tested. One such application being developed is a combination of main propulsion system level diagnostic models with detailed engine diagnostic models. This experiment, originally intended for the X-34 vehicle, is being migrated and further developed for the Space Launch Initiative Program.

Another Propulsion IVHM project was the successful design, development and implementation of an automated Post-Test Diagnostic System (PTDS) for the X-33 linear aerospike engine. This system was designed to reduce analysis time and to increase the accuracy and repeatability of rocket engine ground test firing and flight data analysis. Rocketdyne estimated that the complete PTDS will reduce routine test turnaround time from 320 hours to 25 hours, and that the PTDS would impact X33 flight turnaround by at least an order of magnitude. Even though the PTDS never was placed into full operation on the X-33 vehicle, the initial system supported all component and engine tests. It successfully assisted engineers in troubleshooting both data acquisition and test article anomalies.

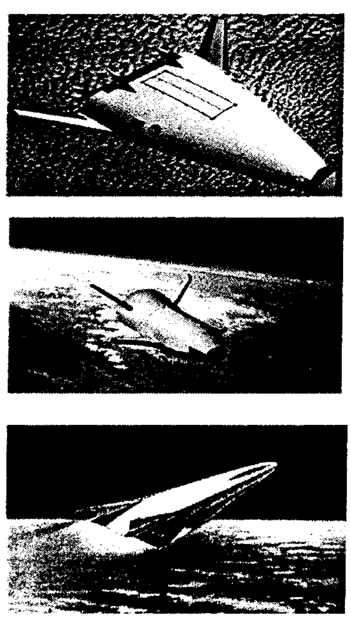
Figure 6. IVHM Technologies Identified by Industry.

Propulsion/Engine/OMS
- Automated Data Analysis
- Condition based maintenance
- Advanced Real-time Anomaly Detection
- Advanced Instrumentation -MEMS, Hi temp, plum spec, high freq
- On-Board Automated Leak detection

Thermal Protection
- MEMs Temp/Pressure Sensors for Overgap Filling
- Real-Time Smart TPS Diagnostic SW

Airframe Structure
- Flight Fiber Optic (FO) Tunable Lasers
- Real-time Dynamic FO Measurements
- Acoustic Emission/Acoustic Ultrasound
- Advanced low/high temp sensitivity

Crew System
- Crew Monitoring/Diagnostic Systems
- Human-centered computing (HCC) Crew Smart Sensor Algorithms



Sources: ISTP, STAS Contracts, Industry Discussions, NRA 8-27, In-House NASA Call, SBIR

Avionics
- Non-intrusive high response Pressure, Temp, PI, Strain, Accels
- Fiber Optic Network Management SW
- Wireless High Speed Data Mgmt
- Multi-tasked/cause-effect data mining
- Multi-use Smart Sensor Algorithms
- Distributed decision-making software
- Vehicle and Subsystem MBR Tech
- Automated feature recognition
- Real-time fault prediction software
- Reprogrammable/Reconfigurable FDIR
- Automated software V&V technologies.
- Auto mission planners/schedulers

Ground System
- Advanced Launch/Mission Diagnostics/Prog
- Automated ground-based maintenance planners/schedulers/work order generator
- Facility Automated Leak detection Hand-Held Portable Maintenance Aid HW
- Automated TPS/Airframe NDE/NDI

TECHNICAL CHALLENGES

IVHM technologies must be applied throughout the vehicle life cycle from conception to operation for optimal benefit. Retrofitting of existing vehicles provides limited benefit and is less cost effective. The design phase must include complete systems engineering of the IVHM technologies including requirements definition, trade studies, risk assessment, cost benefit analysis, etc. The analysis must be carried out at the subsystem level as well as at the vehicle level.

The design must consider minimized cost and enhanced safety for all phases of operation as well – including ground processing, mission ops, flight ops, sustaining engineering and program development.

Figure 6 shows the technologies and subsystems that will be required for a true IVHM system. The challenges of these technologies include:

Increase Knowledge of Health State of Vehicle System

- Data collection is currently "expensive" (weight, reliability, failure modes)
- Data management is limited by telemetry bandwidth, capability of sensor systems, computational power, highly dependent on human expertise

Increase Capability to Use Knowledge to Improve Safety & Reliability

- Limited FDIR (fault detection, isolation, repair)
- Conservative preventive and corrective maintenance strategies
- Limited prognostic capability
- Limited proactive, real-time solutions to health problems

Increase Margins, Operating Ranges

- Extreme environments
- Life limits on existing components

SUMMARY

IVHM has the potential to reduce, or even eliminate, many of the costly inspections and operations activities required by future space transportation systems. The development and utilization of an effective and operable IVHM is dependent on the availability of highly reliable sensors and decision-making software. The commercial world (i.e., the automotive industry), in order to facilitate moving forward with technological development, has had to make essentially revolutionary (from their viewpoint) modifications in their design philosophies to stay in business, never mind keep up. So must NASA.

ACKNOWLEDGEMENTS

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